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An overview of different distillation methods for small scale applications

R. Saidur[a,*], E.T. Elcevvadi[a], S. Mekhilef[b], A. Safari[b], H.A. Mohammed[c]

[a] Department of Mechanical Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia
[b] Department of Electrical Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia
[c] Department of Mechanical Engineering, College of Engineering, Universiti Tenaga Nasional, Km 7, Jalan Kajang-Puchong, 43009 Kajang, Selangor, Malaysia

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ABSTRACT

Many countries now suffer from shortage in fresh water, hence, currently 125 countries around the world are taking advantage of desalination methods to access fresh water from brackish and seawater. As desalination is one of the important processes for producing potable water that can be used for human consumption, irrigation and industry. In the last decades, many researchers have been conducted to minimize the cost of this process, and several methods have been developed. Among these methods, distillation appears as one of the best practical and the most economical, especially for mass production of fresh water from high saline water like seawater. On the other hand, most of the ongoing desalination researches concentrate on large-scale plants which are suitable for mass production of fresh water. A few researches have been conducted on small scale water distillation. This study will focus on different distillation methods for small scale production of potable water which is suitable for domestic, small factories, laboratories, and emergency use. This review presents various technologies available for small scale distillation with focus on Refro-distiller systems. Consequently, the theoretical analysis to determine the efficiency and energy costs are presented.

Contents

1. Introduction

Due to the rapid increase in the population number and the fast growth in the industrial and agricultural fields, clean water supply has become a necessary requirement in the modern life. Many countries now suffer from shortage in fresh water and the amount of fresh water in many reserves is decreasing alarmingly. Moreover, waste water coming from the industrial factories and plants, and sewage from large cities pollute the remaining fresh water resources. Fig. 1 shows that only 0.5% of earth's water is fresh water and 2% is glaciers and icecaps, while seawater distribute to 97% of the water available on the earth [1–3].

Oceans and seas are the largest reserves of water; however, due to their high salt concentration, they are not suitable for the human

* Corresponding author. Tel.: +603 79674462; fax: +603 79675317.
E-mail addresses: saidur912@yahoo.com, saidur@um.edu.my (R. Saidur).

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Nomenclature

UAE	United Arab Emirates
IDA	International Desalination Association
MSF	multi stage flash
TBT	top brine temperature
MED	multiple effect distillation
VCD	vapour compression distillation
LMTD	log-mean temperature difference
SGHT	symmetric green house type
ASGHT	asymmetric green house type
GFL	Gesellschaft fur Labortechnik
COP	coefficient of performance

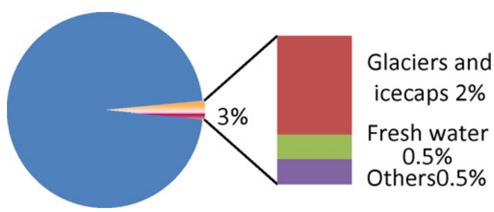

Fig. 1. Earth's water distribution.

use. Therefore, desalination has become an important technique to provide fresh water in many countries, especially in the Middle East and North Africa where most of their lands are deserts with plenty of energy sources [1]. Some countries in these regions such as Saudi Arabia, United Arab Emirates (UAE) and Kuwait are the leaders in this industry worldwide. It is estimated that more than 75 million people around the world use seawater or brackish water desalination for their needs [3]. Based on the global statistics released by International Desalination Association's (IDA) Desalting Inventory, saline water desalination plants has been reached 17,348 units in 2004 with a capacity of 37.75 million m^3/day of fresh water from 10,350 units in 2002 [4]. The recent capacity of the global desalination plant is 40 million m^3/day and the yearly average growth rate for the last 5 years is 12% [5].

The five leading countries in desalination industry are shown in Fig. 2. The Jabal Ali desalination plant in its second phase, which is dual-purpose facility in the UAE, is considered to be the largest in the world, utilizing a capacity of 300 million cubic meters of water per year in multi-stage flash (MSF) distillation. The United States' biggest desalination facility, situated at Tampa Bay, Florida, set off desalting at a capacity of 95,000 m^3/day in 2007 [6].

In almost all desalinated water sources in the world, seawater makes up about 60% while brackish water reaches 40% [4]. As desalination is one of the important processes for producing potable water that can be used for human consumption, irrigation and industry, in the last decades, many researchers have been conducted to minimize the cost of this process, and several methods have been achieved. Among these methods distillation appears

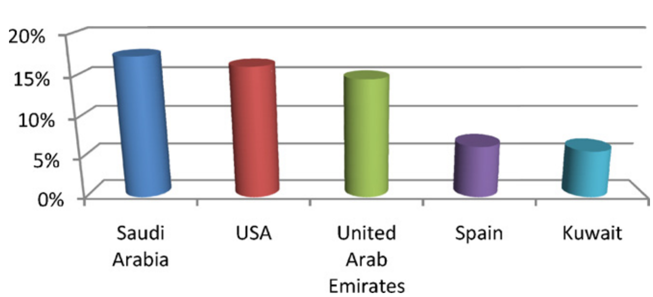

Fig. 2. Five world leading countries by desalination capacity.

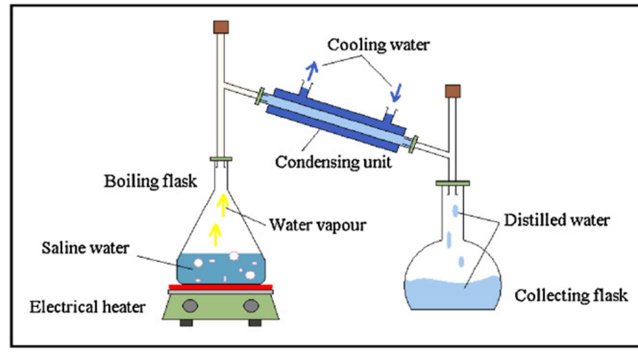

Fig. 3. Distillation traditional method [8].

as one of the best practical and the most economic, especially for mass production of fresh water from high saline water like seawater [3,7]. On the other hand, most of the ongoing desalination researches concentrate on large-scale plants which are suitable for mass production of fresh water. A few researches have been conducted on small scale water distillation. This study will focus on different distillation methods for small scale production of potable water which is suitable for domestic, small factories, laboratories, and emergency use.

2. Distillation methods

All distillation techniques are based on a similar working principle. The water and the dissolved gases in it are able to volatile during boiling saline water, while the minerals and the dissolved salts are not evaporating easily unless for boiling temperatures above 300 °C. Thus, in all practical distillation methods, it is assumed that during boiling saline water, only pure water vapour and some of the dissolved gases will come out while the remaining salts and minerals will stay behind. Consequently, during condensation merely the vapour water will condense to clean pure distilled water [7]. There are several distillation methods developed for water desalination technology which differ in simplicity, cost and applications.

2.1. Simple traditional distillation

The traditional method is the simplest way to distil salty water but at the same time it is the most expensive type in terms of energy consumption. This way of distilling water is commonly used in chemical laboratories as well as domestic applications. Working principle of this method is illustrated in Fig. 3.

In this method, the saline water in the boiling flask is heated to start boiling and evaporating by a heat source (electrical heater, natural gas stove, oil stove, solar plate or any other kind of heat source). The water vapour will go towards the condensing unit which is cooled by separate cooling water. Thus, the water vapour will lose some of its latent heat and it will change from the gaseous state (vapour) to liquid state (pure distilled water). The water droplets will combine with each other and move towards the collecting flask [8].

This method suffers from requesting a very large amount of energy to evaporate the saline water due to the high latent heat of water vaporization of about 2257 kJ/kg at 100 °C. As a result, the traditional distillation method is suitable only for desalinating a small amount of saline water [9].

2.2. Single stage distillation

The principle operation of the single stage distillation method is illustrated in Fig. 4.

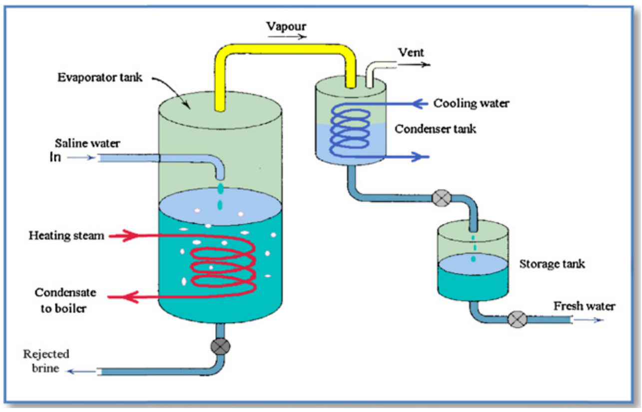

Fig. 4. The single stage distillation system [7].

In the single stage distillation system, the evaporator tank is fed by saline water through the saline water pipe. The saline water is then heated by passing a hot steam through the steam heat exchanger, located in the evaporator tank, until it reaches the boiling temperature. The steam will pass through the tubes of the heat exchanger, condenses and returns back to the boiler while the saline water outside the tubes boils, and thus, evaporates. The water vapour rises and moves towards the condenser tank. In the condenser tank, the water vapour is cooled down by passing cold water through some cooling pipes. Thus, the water vapour will turn to pure liquid water. Subsequently, the distilled water will be collected and stored in the storage tank. To ensure that the heat released from the heating steam, will flow towards the saline water, the condensation temperature of steam has to be higher than the boiling temperature of the saline water. To achieve that, the saline water boiling temperature is reduced by decreasing its vapour pressure. The vapour pressure is controlled by venting the air from the evaporator tank by a vacuum pump or an ejector.

The remaining brine water is removed from the evaporator tank continuously during the distillation process or intermittently at the end of each process. The salt concentration in the brine is much higher than the saline feed water and it is usually two times higher than the feed water in seawater distillation [7].

The single stage distillation process is considered to be a good choice for saline water distillation when the compact size of a plant is important. This method is suitable for marine application and big laboratories. It is also a suitable choice when the heating steam is abundant and cheap, like in co-generation applications with other electrical power plants or factories [10].

Ref. [11] has evaluated the flow rate of a single stage distillation process to produce fresh water when temperature and salt concentrations are changed. A single effect system with constant pressure of 80 mmHg has been utilized to control the operational conditions of the distillation process, under variable evaporation temperature and salt concentration. It has been confirmed that the production of fresh water depends on temperature and salt concentration whose effects are more significant as the temperature rises and salt concentration lowers. Distilled water production can be increased to 100% by augmenting the saline water temperature, whereas lowering the salt and brine water concentration can increase it by 33%.

2.3. Multiple effect distillation

Due to the necessity to use a large amount of heat in order to evaporate the saline water by utilizing the previous methods, scientists and engineers have developed other methods to recover the heat released from water vapour during vapour condensation process. The aim is to utilize same amount of heat to evaporate more amounts of saline water, increase water distillation plant efficiency and reduces their running energy costs. One of the important methods that utilize the heat recovery principle is the multiple effect distillation method [7].

Fig. 5 shows a simple diagram of a multiple effect distillation system which consists of four evaporators, one boiler and one condenser.

In multiple effect distillation method, the water is boiled in the boiler and is converted to hot steam. The hot steam will boil the saline water in the first evaporator. The vapour coming out from the first evaporator will act as a heating medium for the second evaporator and will boil the saline water there. The vapour coming out from the second evaporator, also, boils the saline water in the third evaporator, and so on. At the same time, the boiling saline water in the fourth evaporator serves as a condensing medium for the vapour coming from the third evaporator. The boiling saline water, at the third evaporator, acts as a condensing medium for the second evaporator vapour and the second evaporator acts as a condenser for the first evaporator vapour. In this method, a large latent heat of vapour condensation is reused several times before releasing it to the surroundings. In such series, each evaporator is called an effect. It is always necessary to keep the first effect at a temperature below the boiler heating steam. Practically, to obtain a good

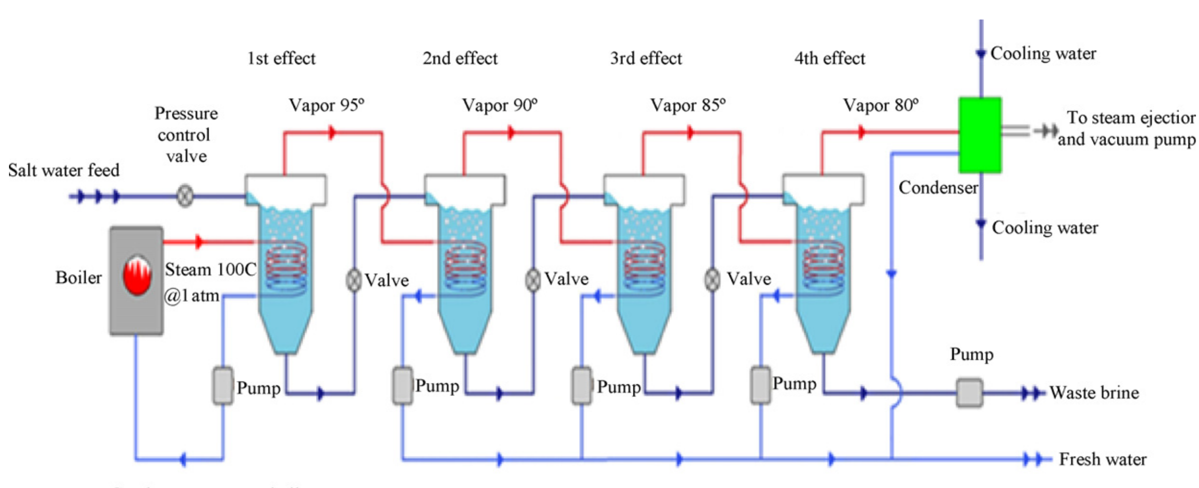

Fig. 5. Multiple effect distillation [7].

heat flow between the heating vapour and the saline boiling water in each effect, it is important to keep them at different degrees of temperature. In other words, the vapour pressure in each effect has to be lower than the vapour pressure in the previous effect and higher than the next effect [3,7].

Due to the effects' pressures below the atmospheric pressure, it is important to equip the system with water pumps to restore the desalinated water at the ambient pressure. Moreover, vacuum pumps are needed to evacuate the vapour space until it reaches the designed pressure, and to exhaust the non-condensing gases such as oxygen and nitrogen. These gases are naturally dissolved in the feed saline water. During the boiling processes, oxygen and nitrogen start to come out and accumulate in the vapour space. If they continue to accumulate, their pressure will increase until it blocks the water boiling, and thus, stops the overall distillation process. Therefore, the vapour spaces in all effects are connected to a steam ejector coupled with a vacuum pump and these vacuum pumps must keep working continuously or intermittently during distillation. To regulate the effects' pressures, throttling pressure valves have been installed between effects. Fig. 5 illustrates the multiple effect distillation and the connection between effects; however, the connection of the steam ejector and the vacuum pumps are not illustrated in this figure.

The multiple effect evaporation helps to produce more than 1 ton of distilled water per ton of heating steam. With the same amount of heating steam, pure water increases as the number of effects increase. The profitability of multiple effect desalination plants is proportionate to the number of the effects. As the number of effects rises, the required heating steam decreases per ton of produced distilled water; however, the initial cost of this process is high when the number of effects increases. The relation between the running costs and initial costs determine the optimal size of the plant. It is noteworthy that total temperature range available and the minimum temperature difference between effects confines the total number of effects [3,7]. An exemplary large plant requires 4–21 effects and performance ratio from 10 to 18 [12,13] found that if plants operate with a top brine temperature (TBT) in the first effect of about 70 °C, they reduce the potential for scaling of seawater; however, at the same time, it will increase the required heat transfer area of the heating tubes. The increase of the size of low temperature MED units has been continuously gradual. Each of the Sharjah's two MED distillation plants in the UAE has a capacity of 22,700 m^3/day. In addition, a module with capacity of 45,400 m^3/day has been designed and demonstrated for the MED process [14].

2.4. Multiple stage flash distillation

In multiple stage flash distillation method, heating and boiling process happens in the same vessel. Some scale forms only during the heating process, but boiling has a greater effect on forming scale than heating on the heat transfer surfaces. Saline water is heated outside the boiling chamber where it is made to evaporate by lowering pressure. Hence, scale remains in the brine instead of on the heating surface. The temperature of seawater increases gradually due to the latent heat of condensation flowing from the condensing water vapour. The saline water is heated in the brine heater by a low pressure steam externally provided from a steam turbine power plant [15] or a cogeneration power plant like a gas turbine with a heat recovery steam generator [16,17]. The heated saline water then flows into the evaporator flash chambers (stages). The evaporator is made of multi-stages, typically containing 19–28 stages in modern large MSF plants [18]. The MSF plants usually operate at top brine temperatures of 90–120 °C, depending on the scale control method selected [3]. Operating the plant at higher temperature limits of 120 °C tends to increase the efficiency, but it also increases the potential for scale formation [19] and accelerated corrosion of metal surfaces in contact with seawater. The vapour pressure determines the water vapour formation quantity in each stage (exemplary boiling saline water drops between 2 °C and 5 °C in each stage depending on the number of stages). Higher number of stages increases the efficiency, but it also increases the capital cost to establish a distillation plant. The value of the production rate determines the water production cost. The production rates range between 6.5 and 10.5 lbs/1000 Btu heat-input for modern large MSF plants [17]. It is proposed that although flash evaporators are seemingly inefficient method due to the water cooling off when a small fraction of it evaporates, its minimal size of scale makes it close to the regular multiple effect distillation [3,7]. Multiple flash distillation process is illustrated in Fig. 6(a)–(c).

Multi stage flash (MSF) has accounted for 36.5% of the total capacity of established desalination plants for brackish and seawater in 2002. For seawater desalination only, MSF reserves the first place in all plants making more than 5000 m^3/day of fresh water [3]. Regenerative heating helps to improve the economic features of the MSF technology because the feed saline water acquires some of the heat given up by the flashing (boiling) seawater in each stage.

In 1950s, the world witnessed the beginning of building MSF plants [20]. In 1953, the United States Navy paved the way towards constructing MSF plants by building a 5 stage MSF plant with capacity of 189 m^3/day. In 1957, four units were installed in Kuwait with capacity of each 2271 m^3 per day [21]. The Shuweiat Plant, located in the UAE is the biggest MSF unit with a production capacity of 75,700 m^3 per day [3]. The world's largest plant "The Saline Water Conversion Corporation" is in Al-Jubail, Saudi Arabia, with capacity of 815,120 m^3 per day [22].

2.5. Vapour compression distillation

In multiple effect distillation (MED) and multiple stage flash (MSF) methods an external source of heat, like crude oil, natural gas, etc., is used to warm up the incoming saline water, whereas the energy needed to heat the saline water in the vapour compression distillation (VCD) method comes from a mechanical source which is the vapour compressor [23]. Vapour compression distillation with one effect is as beneficial as a 15–20 effect MED method [7]. Fig. 7 describes the main idea behind the vapour compression distillation. Saline water is preheated in a horizontal heat exchanger, located outside the evaporator, by the leaving streams of distilled and brine water. Then, the saline feed water boils inside the tubes of the evaporator. The resulting water vapour is compressed by an external mechanical compressor. Subsequently, the hot compressed water vapour is fed back to the evaporator to be condensed outside the tubes and provide the required heating energy for the boiling saline water. A vacuum pump or ejector withdraws non-condensing gases such as nitrogen, oxygen and dioxide carbon from the evaporator/condenser space [7].

Bahar et al. [24] have carried out a series of experiments on a mechanical vapour compression water distiller pilot plant with two vertical evaporator/condensers and average capacity of 1 m^3 per day. A maximum number of the plant performance ratio of 2.52 has been set up. Performance of the pilot plant has been assessed under variant compressor speeds and different magnitudes of brine concentrations ranging from 20,000 ppm to 33,000 ppm. The maximum brine temperature was set at 103 °C. The results show that decreasing the brine concentration and increasing the compressor speed will increase the performance of the mechanical vapour compression pilot plant.

Aybar [25] has analyzed the operation features for a low-temperature mechanical vapour compression distillation system. The proposed system had a single tube with a 0.025 m diameter and a 9.0 m length. To improve and optimize the design three

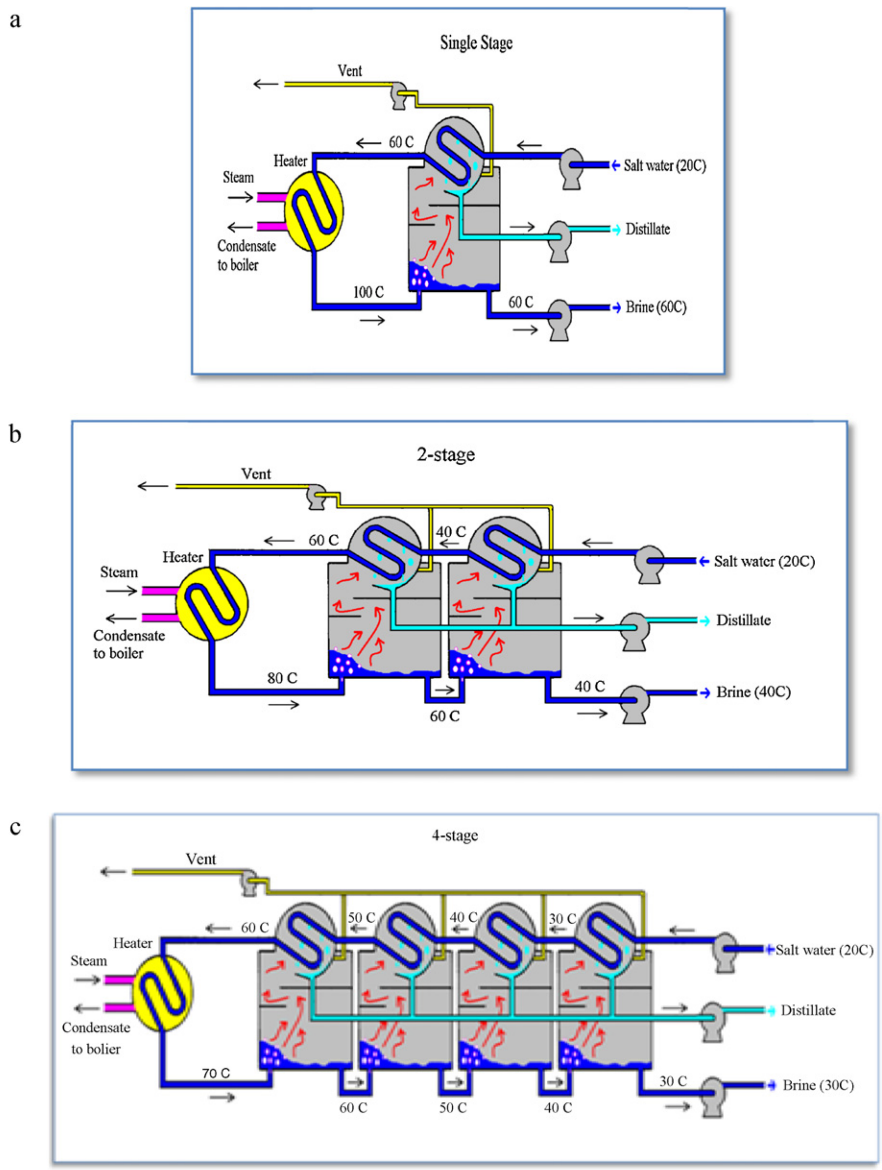

Fig. 6. (a) 1 stage flash distillation [3]. (b) 2 stage flash distillation [3], and (c) 4 stage flash distillation [3].

approaches has been considered; the overall energy balance equations, the mass balance equations and the log-mean temperature difference (LMTD) method for the heat transfer calculations. It was resulted that when the saline feed water inlet temperature is hotter than the evaporation saturation temperature, the performance of the machine will be increased. The optimum parameters of proposed system are described in Table 1.

In the proposed system, the specific energy consumption was 11.47 kWh per ton of fresh water. Therefore, for a capacity of 250

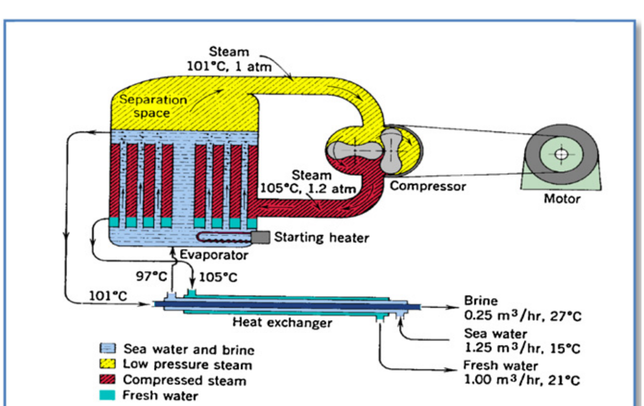

Fig. 7. Vapour compression distillation method [7].

Table 1
Optimum operation data for a mechanical vapour compression water distiller [25].

Parameters	Value
Evaporation side pressure, kPa	50.0 (T_{sat} = 81.35 °C)
Condensation side pressure, kPa	62.5 (T_{sat} = 87.00 °C)
Pressure gradient, kPa	12.5
Water inlet temperature, °C	85
Evaporation side inlet temperature, °C	81.35
Evaporation side outlet temperature, °C	81.35
Condensation side inlet temperature, °C	103.17
Condensation side outlet temperature, °C	87
Compressor work, W	85.83
Heat transfer rate, W	4756.24
Mass flow rate per tube, kg/s	0.002077
Specific energy consumption, kWh/ton	11.47
Nominal power consumption for 250 ton water/day, kW	119.57

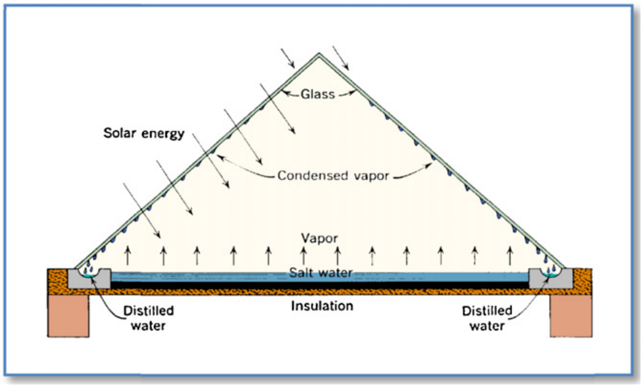

Fig. 8. Symmetric greenhouse type (SGHT) solar still [26].

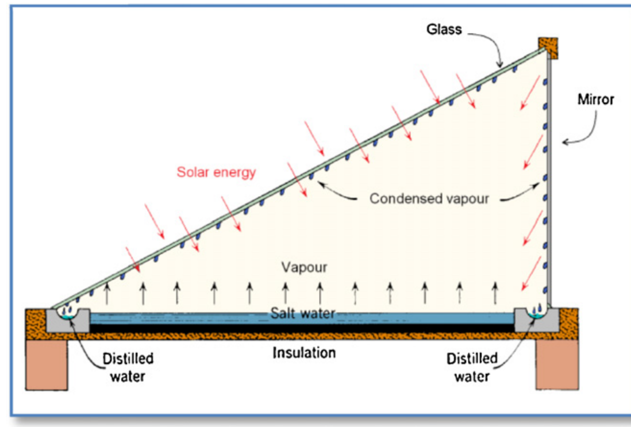

Fig. 9. Asymmetrical greenhouse type (ASGHT) solar still [26].

ton fresh water per day, 1393 tubes are needed. Each tube is 9 m length with nominal power consumption equal to 119.57 kW [25].

3. Solar distillation

Most of the running expenditure for the various distillation methods lies under the high energy cost of the evaporation process. Solar distillation looks very attractive due to utilizing the heat of the sun since it is a free source of energy. Solar water distillation has begun over a century ago. In 1872, a solar plant with capacity around 4000 m^2 has been built in Chile and successfully ran for many years. In addition, the small plastic solar stills have been employed to provide potable water for life rafts floating in the ocean during World War II.

In this method, the saline water is fed to a black plate located in the lower portion of the solar distiller. The heat of the sun causes the saline water to evaporate. When water vapour reaches the cool transparent leaning surface which is usually made of glass or plastic, it condenses to form purely distilled droplets of water. The droplets grow up until they become heavy enough to slide down along the leaning surface. The water droplets are collected through special channels located under the leaning surface. Eventually, the fresh water runs inside the channels to reach the fresh water tank.

Al-Hayeka and Badran [26] have studied the effect of using different types of solar stills on distilled water production. The overall performance of two types of solar water distillers has been compared:

- Symmetric greenhouse type (SGHT) which has no additional mirrors.
- Asymmetric greenhouse type (ASGHT) which has additional mirrors on its internal walls.

Figs. 8 and 9 depict the symmetric and asymmetric greenhouse types, respectively.

Efficiency of the asymmetric systems is 20% higher than symmetric. Moreover, decreasing the saline water depth in the evaporator plate and adding a dye on the saline water increases the amount of fresh water produced [26].

Abdel Dayem [27] has designed and implemented a more complicated solar distillation system with a better performance. A humidifier and dehumidifier units are added to the system components. The proposed solar system is consist of solar collector, heat exchanger, heater tank, and flashing unit or distillation chamber, which is made up of a humidifier (evaporator) and dehumidifier (condenser). In the distillation chamber, the humid air circulates between the humidifier and dehumidifier by the mean of natural conviction. The solar collector plate area is 3.1 m^3. Throughout the numerical analyses, it was found that the optimum area for the solar plate should be equal to 6 m^3. After running the experiment, the amount of distilled water produced per day was 24 l for a normal sunny day [27].

4. Refro-distiller-a new method

Most of the small scale water distillers which are suitable for domestic, laboratory and emergency applications utilize either the reverse osmoses or the simple traditional distillation method for water desalination [28]. In small scale applications the reverse osmoses method is suitable for desalination when the feed water is not highly saline and the desalinate water (output) is not needed to be in very high purity [29,30]. Many laboratories, hospitals, pharmacies and houses located in areas with salty water prefer to use the simple traditional distillation for their needs. For instance, Bakhsh Hospital in Makkah in Saudi Arabia uses GFL (Gesellschaft fur Labortechnik mbH) water distiller which utilizes the simple traditional technique. Fig. 10(a) and (b) has been snapped in 2009.

The simple traditional method requires high running cost of its energy consumption, due to large enthalpy needed to transfer water from the liquid state to the gaseous state (vapour). Moreover, additional energy is needed to increase water temperature to reach the boiling temperature (100 °C). Theoretically, if evaporation is required for 1 kg of water at room temperature (25 °C), then 314.34 kJ is needed to raise the temperature to 100 °C and 2256.4 kJ to evaporate the water [9]. Thus, the total required heat is equal to 2570.7 kJ, which is actually a large amount of energy; however, a system with a good heat recovery and low pressure condition can save a significant amount of heat needed to evaporate water under normal condition [11]. The Refro-distiller utilizes two features: first, heat recovery mechanism to minimize the waste heat lost during traditional distillation, and second, a low pressure condition to decrease the boiling temperature.

4.1. Working principle

The Refro-distiller uses a normal refrigeration cycle for cooling and heating, and thus saves a great amount of electrical energy compared with traditional distillers which use electrical heaters. The coefficient of performance (COP) of an ideal vapour compression refrigeration cycle is usually around 4. In other words, theoretically, the Refro-distiller should transfer thermal energy required to heat and evaporate water, which is 4 times the electrical energy the Refro-distiller consumes. Vice versa, the efficiency of the ideal electrical heaters, used in the traditional distillers, is about 100%. It means that ideal electrical heaters in distillers utilize

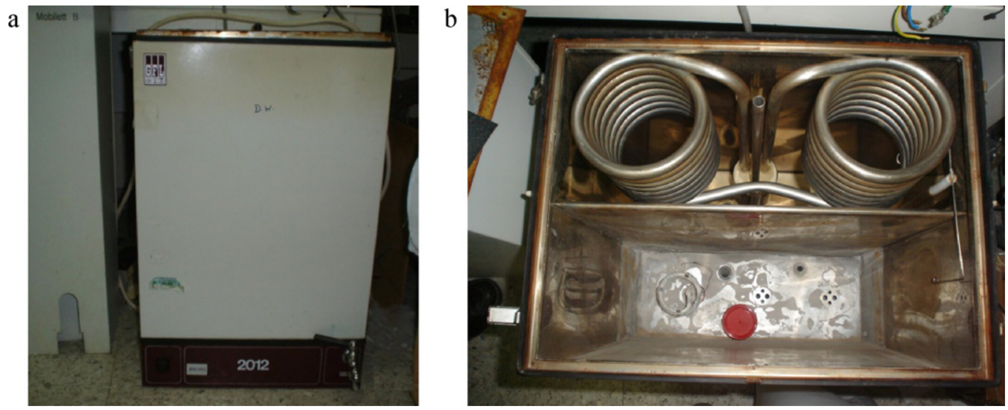

Fig. 10. GFL Bakhsh Hospital's water distiller using the traditional method.

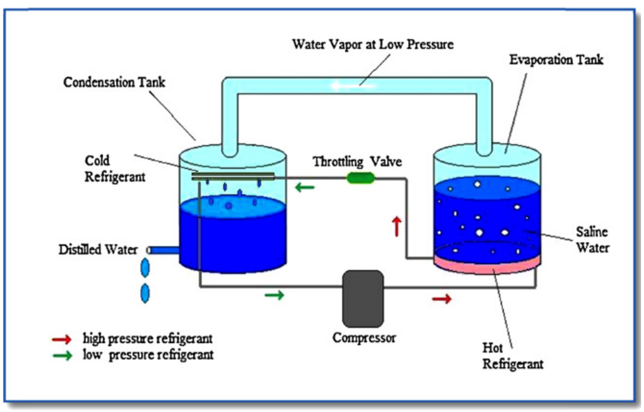

Fig. 11. Working principle of the Refro-distiller [11].

thermal energy in the same amount of electrical energy. Working principle of Refro-distillers is depicted in Fig. 11.

4.2. Types of distillers using refrigeration cycle

Water distillers using refrigeration cycle are classified into two main groups based on the over-all heat cycle; closed loop and the open loop heat cycle.

In the closed loop heat cycle distillers, the heat is re-circulated between the evaporator and the condenser continuously during the process of distillation. Theoretically, if the heat loss can be reduced in a significant amount, then a good level of over-all efficiency can be achieved.

Fig. 12 is an illustration of closed loop distiller. In this scheme, the heat is pumped from the condenser tank towards the evaporator vessel by the refrigeration cycle and will return to the condenser tank by the mass flow of hot vapour coming out from the evaporator tank towards the condenser tank and thus completing the closed heat cycle. The machine that uses closed cycle for water distillation can be called Refro-distiller.

The open loop heat cycle distillers are either hot or cold Refro-distiller. When the temperature of feed water for distillation is above 45 °C, the hot Refro-distiller is needed. The maximum refrigerant temperature in a closed loop heat Refro-distiller is between 50 °C and 60 °C; thus, if feed water is above 45 °C, the machine will gradually stop working in a short time. The solution is to extract heat from feed water directly without heating it. Fig. 13 shows the hot open loop heat cycle Refro-distiller. When hot water enters the evaporator tank, it will be subject to low pressure. This low pressure will stimulate the hot water to start boiling. The vapour coming from the boiling water will move through a connecting pipe to reach the condensing vessel, in which the vapour will collide with a cold coil; and thus, condensation starts. The heat is extracted from the condensation vessel throughout the refrigeration cycle to the surroundings.

Contrary to the hot open loop heat cycle, the cold open loop heat cycle is designed for the cold feed water below 10 °C. The machine using this technology can be referred to as the cold Refro-distiller. In this method, when the cold saline water enters the distiller, it will be preheated in the condenser by exchanging heat with the hot vapour. Then, it will be re-heated in the evaporator tank by the heat which is pumped from the surroundings of refrigeration cycle. Fig. 14 shows the cold open loop heat cycle Refro-distiller.

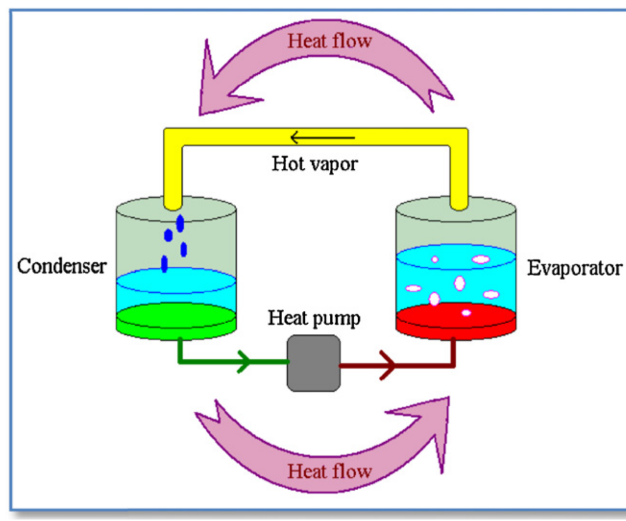

Fig. 12. Heat is circulated between the evaporator and the condenser [11].

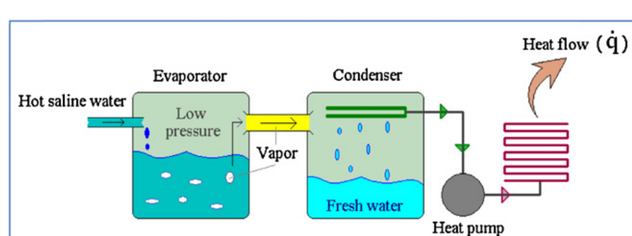

Fig. 13. The hot open loop heat cycle Refro-distiller.

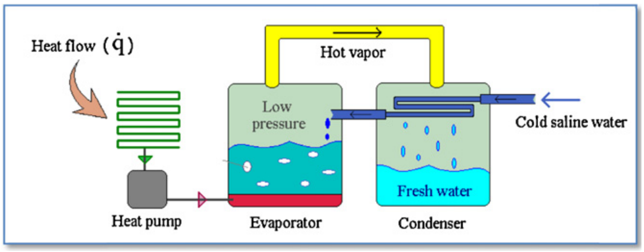

Fig. 14. The cold open loop heat cycle Refro-distiller.

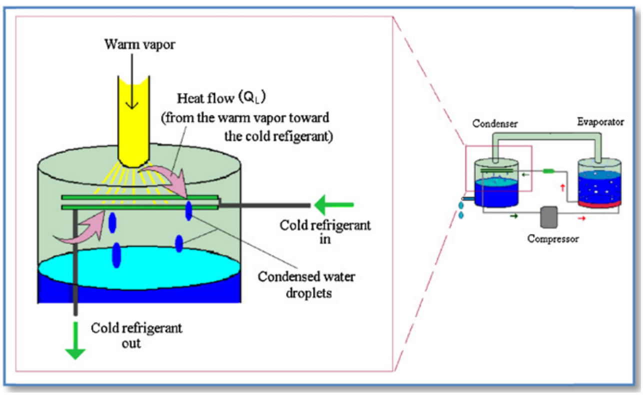

Fig. 15. Condensation process.

4.3. Theoretical analysis

To calculate the production rate (efficiency) of a distilled water system and the cost of energy, it is worth-understanding that the main part of the Refro-distiller is the refrigeration cycle. Two methods have been developed to calculate the distilled water production rate and the energy cost; the ideal vapour compression refrigeration cycle and the experimental method. The condensation process for the water vapour occurs at the condenser tank around the cold pipe. Therefore, the amount of condensed water mainly depends on the amount of heat (Q_L) which is removed from the vapour towards the cold pipe. Fig. 15 illustrates the condensation process.

To calculate Q_L and the amount of water produced, it is assumed that the refrigeration cycle in the Refro-distiller is an ideal vapour compression refrigeration cycle as shown in Fig. 16.

The ideal cycle consists of the following processes [9]:

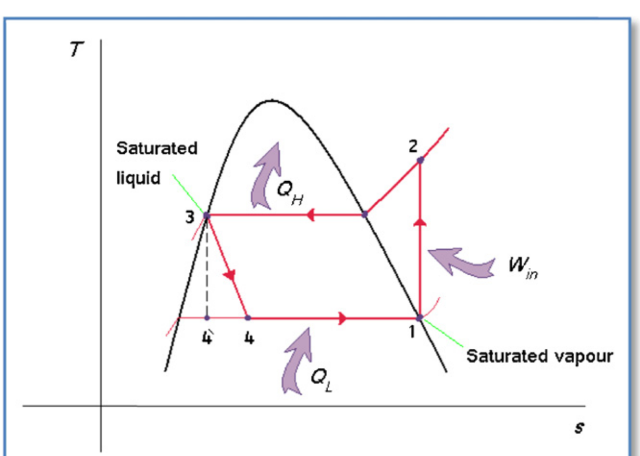

Fig. 16. The ideal vapour compression refrigeration cycle [9].

1-2 Isentropic compression in the compressor.
2-3 Constant pressure heat rejection in the hot pipe.
3-4 Throttling.
4-1 Constant pressure heat absorption in the cold pipe.

Referring to the saturated water-temperature tables, the latent heat of evaporation (h_{fg}) for water, which is the same amount of heat needed to be removed to condense 1 kg of water vapour at 25 °C, is 2441.7 kJ. As a result, the mass of the water produced (m_{water}) is equal to the amount of the removed heat Q_L over h_{fg}.

$$m_{water} = \frac{Q_L \ (kJ)}{h_{fg}} = \frac{Q_L \ (kJ)}{2441.7} \ (kg) \quad (1)$$

Efficiency of a water distiller is:

$$\text{Production rate} \quad (\eta) = \frac{m}{W_{in}} = \frac{Q_L}{W_{in} \times 2441.7} \quad (2)$$

$$\text{Production rate} \quad (\eta) = \frac{COP_R}{2441.7} \quad (3)$$

where m is the output distilled water, W_{in} is the consumed electrical energy and COP_R is the coefficient of performance for the refrigeration cycle. The COP_R for the ideal vapour compression refrigeration cycle and COP_{HP} for heat pumps can be calculated by the following equation [9]:

$$COP_R = \frac{h_1 - h_4}{h_2 - h_1} \quad (4)$$

$$COP_{HP} = \frac{h_2 - h_3}{h_2 - h_1} \quad (5)$$

where h_1 is the refrigerant enthalpy at the beginning of the isentropic compression, h_2 is the refrigerant enthalpy at the end of the isentropic compression, h_3 is the refrigerant enthalpy at the end of the hot pipe and just before entering the throttling valve, h_4 is the refrigerant enthalpy after the throttling valve.

Another significant criterion is the energy cost of the system which is defined as the total energy consumed over the amount of the produced distilled water.

$$E_{cost} = \frac{\text{Total consumed energy}}{m_{water}} \quad (6)$$

For the ideal vapour compression refrigeration cycle energy consumption is equal to the work done by the compressor (W_{in}), hence the energy cost (E_{cost}) is:

$$E_{cos\,t} = \frac{W_{in}}{m_{water}} = \frac{1}{\text{Production rate} \quad (\eta)} \quad (7)$$

The energy cost for the evacuation process of an ideal Refro-distiller can be calculated by:

$$E_{evacuation} = \Delta P \times V \quad (8)$$

where $E_{evacuation}$ is the energy cost needed to evacuate enough space for 1 kg of distilled water, ΔP is the pressure difference between the environment (1 atm) and the saturated pressure of water at 25 °C, V is the volume of 1 kg of distilled water.

5. Conclusion

Distillation proves to be one of the best and the most economical methods for small scale production of fresh water from high saline water like seawater. The main leading methods for water distillation are: normal traditional distillation, single stage distillation, multiple effect distillation, multiple flash distillation, vapour compression distillation, and solar evaporation. These methods are suitable for different size of production. Operating the plant at higher temperature limits of 120 °C tends to increase the efficiency, but it also increases the potential for scale formation and

accelerated corrosion of metal surfaces in contact with seawater in multiple flash distillation process. The simple traditional method has a disadvantage of having high running cost in its energy consumption, due to large enthalpy needed to transfer water from the liquid state to the gaseous state (vapour). Multiple effect distillation (MED) and the multiple stage flash (MSF) utilize an external source of heat, like crude oil, natural gas, etc., to warm up the incoming saline water, whereas the energy needed to heat the saline water in the vapour compression distillation (VCD) comes from a mechanical source which is the vapour compressor. Decreasing the saline water depth in the evaporator plate, and adding a dye on the saline water have increased the production of the fresh water as well. Moreover, additional energy is needed to increase water temperature to reach the boiling temperature (100 °C). The Refro-distiller utilizes heat recovery mechanism to minimize the waste heat lost during traditional distillation, and a low pressure condition to decrease the temperature of boiling.

More researches should be conducted to increase the efficiency of distillation systems utilizing a variable speed compressor, better insulation, improve different types of refrigerant and design a better structural mechanism.

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